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APBF-DEC NOx Adsorber/DPF Project: Light-Duty Passenger Car Platform

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ABSTRACT
A 1.9L turbo direct injection (TDI) diesel engine was modified to achieve the upcoming Tier 2 Bin 5 emission standard in combination with a NOx adsorber catalyst (NAC) and a diesel particulate filter (DPF). The primary objective for developing this test bed is to investigating the effects of different fuel sulfur contents on the performance of an advanced emission control system (ECS) in a light-duty application.

During the development process, the engine-out emissions were minimized by applying a state-of-the-art combustion system in combination with cooled exhaust gas recirculation (EGR). The subsequent calibration effort resulted in emission levels requiring 80-90 percent nitrogen-oxide (NOx) and particulate matter (PM) conversion rates by the corresponding ECS.

The strategy development included ean/rich modulation for NAC regeneration, as well as, the desulfurization of the NAC and the regeneration of the DPF.

Two slightly different ECS were investigated and calibrated. The initial vehicle results in an Audi A4 station wagon over the federal test procedure (FTP), US 06, and the highway fuel economy test (HFET) cycle indicate the potential of these configuration to meet the future Tier 2 emission standard.

INTRODUCTION
Due to a desire to reduce dependence on foreign oil, the diesel engine is becoming a prime candidate for future medium-duty vehicle applications in the US. The diesel engine exhibits high thermal efficiency and superior durability compared to the gasoline engine. The main obstacle to increased use of diesel engines is the upcoming (extremely stringent) EPA Tier 2 emission standards. To succeed, these vehicles must comply with emission standards while maintaining their excellent fuel economy. The availability of technologies such as common rail fuel injection systems, low sulfur diesel fuel, NACs, and DPFs allow the development of powertrain systems with the potential to comply with targeted requirements. In support of this, the US Department of Energy (DOE) has undertaken several test projects as part of their Advanced Petroleum Based Fuels – Diesel Emission Control (APBF-DEC) activity. Primary questions among those addressed by these projects are sulfur tolerance, durability, and performance of the NO_X adsorber/DPF system for varying fuel sulfur levels. The test bed for one project in their activity is an Audi A4 Avant equipped with a 1.9L prototype TDI engine with common rail fuel injection.

While NAC systems have demonstrated extremely high levels of NO_X reduction in steady-state laboratory evaluations, the application of NAC systems to actual transient engine applications requires development of an integrated engine-emissions management system. This paper discusses the integrated engine-emissions system management, and the development of regeneration control strategies. Performance of fresh and aged systems tested over the FTP, HFET, and US06 test cycles will also be summarized, including emissions of regulated and presently unregulated species.

TEST SET-UP
Engine testing was performed using a prototype 1.9L state-of-the-art TDI diesel engine in combination with a customized control system including an electronic control unit (ECU) bypass environment. The engine is turbocharged and intercooled. In addition, it is equipped with a customized cooled EGR system allowing for high

recirculation rates. This is necessary to achieve the lowest possible engine-out NOx emissions required as a base for a successful implementation of the ECS to meet the emission targets. The engine specifications are listed in Table 1.

Table 1: Test Engine Specifications

Arrangement	In-Line 4 Cylinder Engine
Displacement	1.9L
Rated Power	100 kW @ 4,000 rpm
Max. Torque	330 Nm
Bore/Stroke	79.5/95.5 mm
Turbocharger	Garrett GT 17V
Injection System	Bosch Common Rail
Valves	2 Intake/2 Exhaust Valves
Compression Ratio	18.2:1

The engine was instrumented and installed in an engine dynamometer cell. In parallel, one engine was also installed in the Audi A4 station wagon. The specifications of the vehicle are exhibited in Table 2.

Table 2: Vehicle Specifications

Vehicle Mass	1590 kg (3,505 lbs.)
Transmission	5-Speed Manual
Total Length	4544 mm
Total Height	1429 mm
Total Width	1766 mm
Drag Coefficient	0.3

The emission control systems used in this project are specified in Figure 1. The main difference between the two systems is the configuration of the close-coupled pre-catalyst. ECS-A contains a pre-catalyst consisting of a diesel oxidation catalyst (DOC) and a NAC (50/50 split) while the ECS-B concept includes a NAC only maintaining the same pre-catalyst volume.

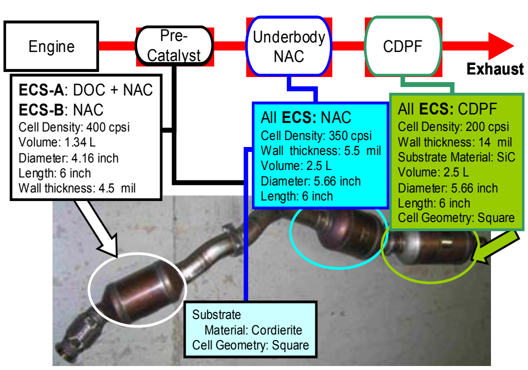

Figure 1: ECS Configuration

Due to the cold start phase and the resulting requirement for an early catalyst light-off the NAC were placed upstream of the DPF. To support the thermal management of the entire system the exhaust manifold was designed as a dual-wall manifold minimizing heat losses. Also the exhaust piping downstream of the turbocharger up to the underbody NAC included a dual wall (air-gap insulation).

The entire exhaust system was also instrumented upstream and downstream of each catalyst with thermocouples for system temperature monitoring and temperature measurement probes as input parameters for the engine control system. Furthermore, NOx sensors were installed between the pre-catalyst and the main underbody NAC as well as between the main underbody NAC and the DPF. Finally, a differential pressure sensor was implemented at the DPF to continuously measure the pressure drop across the DPF as an input parameter for the regeneration strategy.

Emissions including CO, CO_2, HC, NO_x, and O_2 were measured upstream and downstream the individual catalysts to monitor systems performance during all calibration tasks performed in test cell operation.

ENGINE TEST RESULTS

The main focus of the engine investigation concentrated on the following sub-tasks:

- Rapid warm-up
- Lean/rich modulation
- Catalyst mapping
- Desulfurization
- DPF Regeneration

As discussed previously, a quick pre-catalyst light-off is mandatory to meet the emission targets. Therefore, active and passive means to shorten the light-off duration after a direct cold start were investigated. This included the dual wall exhaust manifold and exhaust gas piping as passive means and the following parameters as active means:

- Injection timing retardation
- Throttling

Applying the final rapid warm-up strategy resulted in an exhaust gas temperature of 200°C after 25 seconds at the upstream pre-catalyst and after 48 seconds at the downstream pre-catalyst.

The principal methodology to achieve rich engine operation is illustrated in Figure 2.

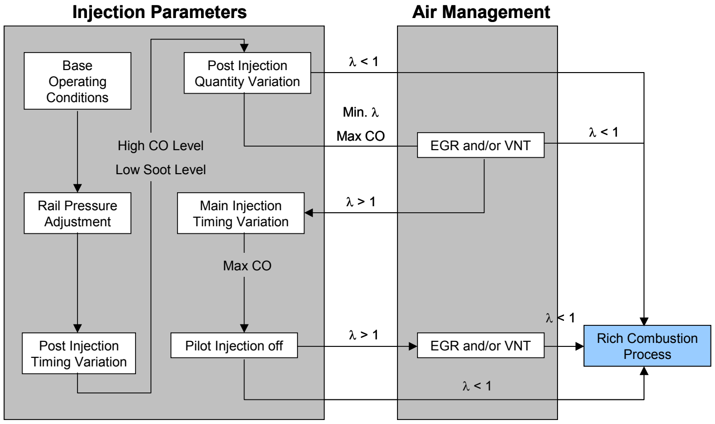

Figure 2: Lean/Rich Modulation Methodology

The lean/rich modulation of a NOx adsorber catalyst is extremely important in many ways. The main characteristics are as following:

- Smooth transition (no noticeable torque fluctuation going rich and back to lean; no noticeable in-/decrease in engine noise)
- Minimized fuel economy penalty
- Generation of sufficient amount of appropriate reactive species for NOx reduction in the subsequent NAC

To achieve a fast, accurate, repeatable and reliable lean/rich modulation, two different paths can be pursued. One possibility is to modify parameters on the intake air side of the engine by throttling, changing boost and EGR, etc. The other and preferred approach is to change the fuel related parameters such as timing and quantity, post injection actuation, and rail pressure adjustment first. The advantage of this approach is the speed and accuracy that these changes can be executed. Only the fuel related parameters cannot be changed to the point that rich engine operation can be achieved, then the intake air side related parameters will be adjusted to complement this process. However, based on the high EGR rates applied to minimize engine-out NOx emissions, the relative air/fuel ratio (lambda) over the cycle (FTP-75, HWFET and US06) relevant operating range is typically at a level that does not require modifications on the air side. In addition to that, it needs to be ensured that the lambda is maintained at a constant and controlled level to avoid deviations of the main characteristics mentioned above.

As a result of the lean/rich investigations multiple maps were established to ensure proper transition from lean to rich and back to lean engine operation and implemented into the bypass environment as a part of the engine control system.

During catalyst mapping, the NAC storage capacity was investigated. This was necessary to monitor the catalyst storage behavior over time due to issues primarily related to thermal deterioration and catalyst poisoning. As a result, the initial storage capacity is used as a baseline for subsequent storage capacity tests to evaluate the degradation of the NAC performance. Figure 3 shows the result of an initial storage capacity check for both the ECS-A and ECS-B system.

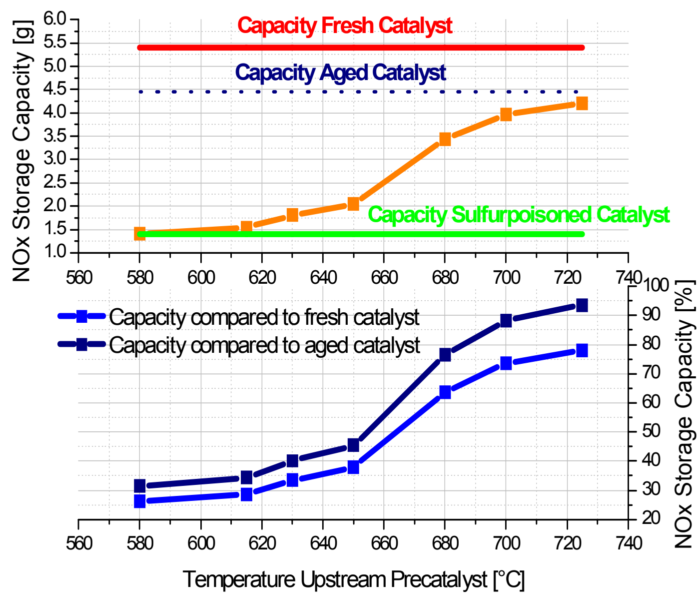

Figure 3: Catalyst Mapping

Based on the NOx storage capacity and the NOx mass flow the lean operation intervals as well as the rich engine operation duration can differ substantially. Different lean/rich timing scenarios NOx conversion ratios between 88% and 96% were identified over the test cycle relevant areas using fresh but degreened catalysts applying the lean/rich strategy as developed during this project.

Since the NAC is extremely vulnerable to sulfur poisoning, strategies to intermittently remove the sulfur from the NAC needed to be established, integrated into the control system, and finally calibrated. Previous investigations [1] have shown that rich engine operation at exhaust temperature levels above 600°C applied over several minutes can result in substantial sulfur removal from the NAC. However, the catalyst formulation also has a significant impact on sulfur release temperature as well as maximum temperature tolerance avoiding excessive thermal aging. Therefore a NAC individual desulfurization strategy and calibration needed to be established to successfully maintain a sufficient NOx conversion ratio to meet the emission targets.

By throttling the intake air in the first stage and applying post injection in the second stage the required lambda and exhaust temperatures can be achieved. During this process, the DOC or the NAC, respectively, within the pre-catalyst have to generate a large portion of the required exotherm. Especially in case of the NAC pre-catalyst the catalyst temperatures need to be monitored closely to eliminate any unnecessary overheating of the catalyst. After the desulfurization is completed, the entire process is reversed and lean operation continues. However, especially when lean operation resumes, the transition from rich to lean is very important. Since HCs adsorbed on the NAC during the desulfurization event will be immediately oxidized when excess oxygen is provided, a temperature spike can be generated which may cause the NAC performance to decline at a much higher rate than expected. Therefore, this transition needs to be conducted at a pace that the HCs can be oxidized slowly and at a controlled rate before conventional lean operation continues.

Results of such an investigation are depicted in Figure 4.

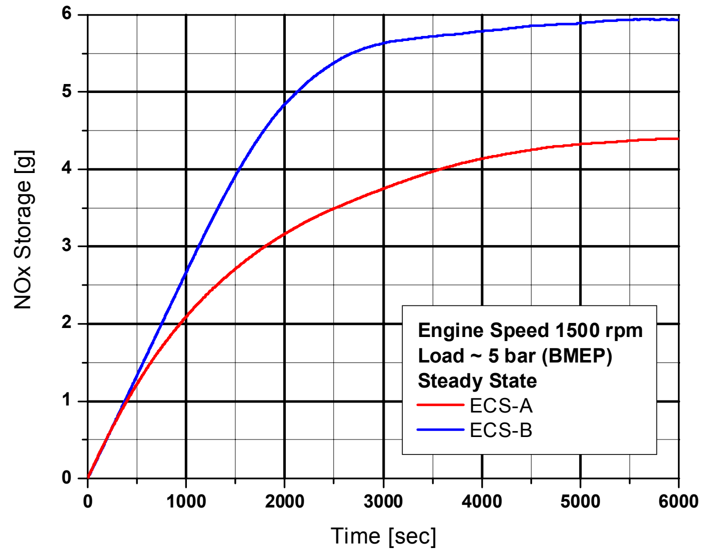

Figure 4: NAC Desulfurization

It can be observed that for the catalyst formulation used the NOx storage capacity recovery is increasing with exhaust gas temperature. A refined version of this strategy is able to achieve desulfurization efficiencies of 95% and higher.

In parallel to the mostly NAC related calibration issues, the DPF regeneration strategy has been developed, integrated, and calibrated. To achieve the required temperature levels for regeneration the engine control system demands a post injection which is used to generate an exotherm across the pre-catalyst and the underbody NAC. Since the DPF is catalytically coated the balance point temperature level could be reduced to approximately 420°C. To implement the DPF behavior into the engine control strategy based on backpressure behavior and corresponding PM loading, the DPF was completely mapped over the relevant cycle area. The results are shown in Figure 5.

It can be observed that at higher PM loadings (10 g/l) at an engine speed of about 3,000 rpm and 10 bar BMEP the balance point can be achieved and the backpressure maintained or even reduced as speed and load are increased further. These are boundary conditions as they can be achieved during some portions of the US06 test cycle based on the speed/load profile the engine is operated under to achieve the vehicle speeds as mandated.

For DPF regeneration events taking place at lower speed/load points the exotherm generated across the pre-catalyst and the underbody NAC need to be controlled to avoid overheating similar to the desulfurization process.

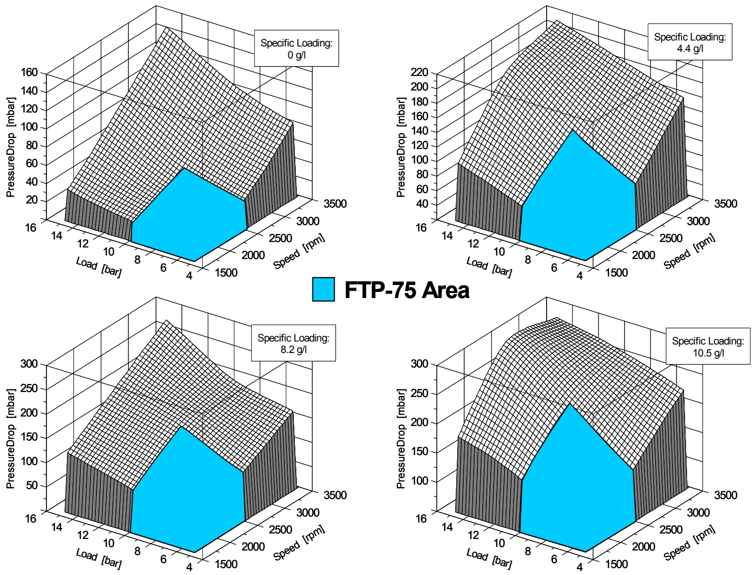

Figure 5: DPF Backpressure Behavior

VEHICLE TEST RESULTS

Vehicle test were conducted at the National Vehicle and Fuel Emissions Laboratory (NVFEL) at EPA in Ann Arbor, Michigan. These tests included the FTP, US06, and HWFET using 0.6 ppm sulfur fuel. Figure 6 shows a comparison of initial ECS-A and ECS-B emissions using fresh (but degreened) or slightly aged catalysts over the FTP test cycle.

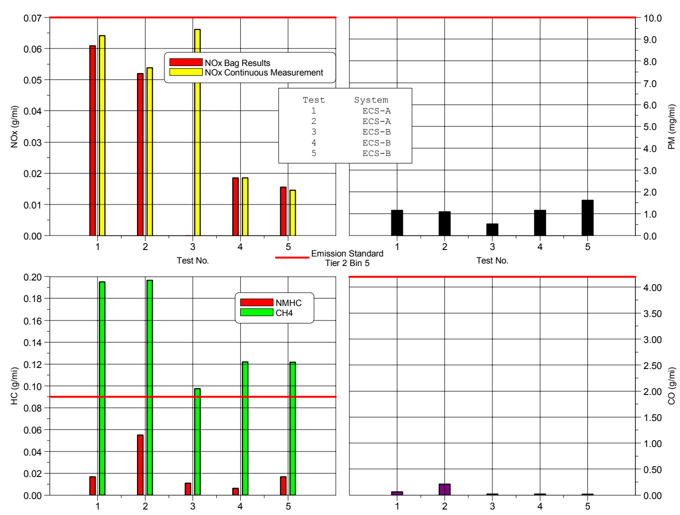

Figure 6: FTP-75 Emission Results

Although these results were achieved using relatively new catalysts, they were very encouraging. Both ECS A and B were able to achieve the targeted emissions for all relevant species. The maximum limits are indicated by the red threshold in each of the individual diagrams. However, based on the higher NOx storage capacity of ECS-B versus ECS-A, the ECS-B was able to achieve even better performance especially regarding NOx emissions. This is mostly related to the improved cold start behavior and the larger NAC pre-catalyst portion. The methane emissions are also shown together with the HCs indicating that the system is generating more methane than usual due to the temporary rich engine operation during NAC regeneration.

The associated fuel economy (FE) numbers and fuel consumption (FC) are shown in Figure 7 below.

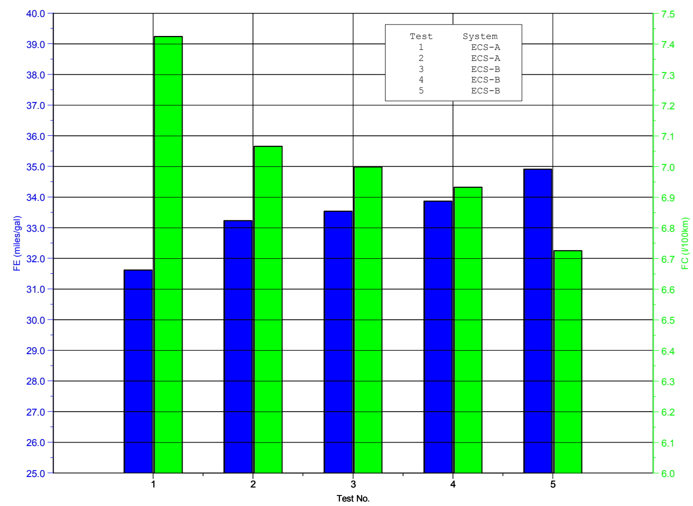

Figure 7: Fuel Economy/Consumption over FTP-75

Despite the continuously decreased NOx emissions during test 4 and 5 the fuel consumption could be further decreased or the fuel economy further increased, respectively. This was possible by refining the NAC regeneration initiation strategy resulting in a more efficient regeneration process.

Test results for the US06 test cycle are illustrated in Figure 8. This test cycle is much more aggressive compared to the FTP-75 cycle resulting in significantly higher NOx emissions as depicted. During test No.6 the mat material of the DPF exhibited some blow-by resulting in increased PM numbers. After replacing the mat material the PM emissions came back to the average level of approximately 3 mg/mi for the ECS-B.

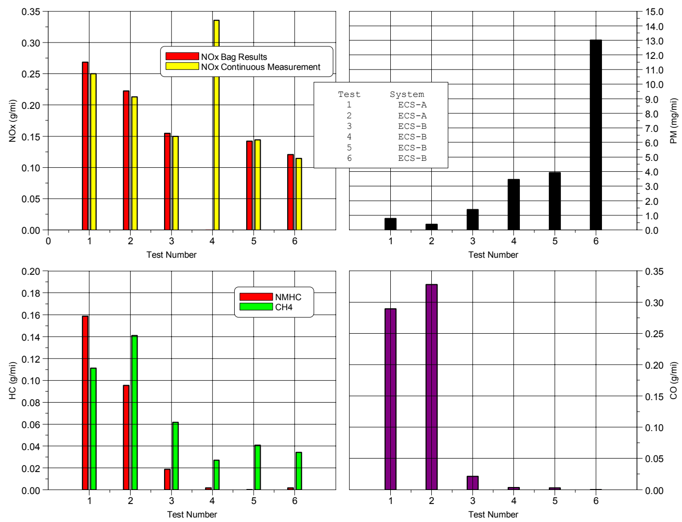

Figure 8: US06 Emission Results

The corresponding fuel economy and fuel consumption results are depicted in Figure 9 below.

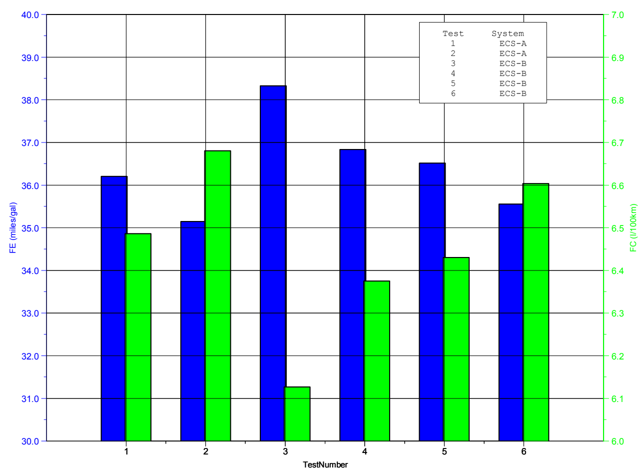

Figure 9: Fuel Economy/Consumption over US06

Despite the relatively heavy vehicle in combination with the 1.9L engine, the fuel economy/consumption could be maintained at a competitive level. This was also confirmed by the HFET tests conducted as part of the testing program.

CONCLUSIONS

Meeting the future Tier 2 emission levels with an un-aged emission control systems has been shown. This required the utilization of state-of-the-art technology such as a TDI diesel engine optimized for lowest possible engine-out NO_x emissions, advanced thermal management including active means (throttling, post injection, etc.) and passive means (dual wall insulation), as well as sophisticated emission control systems. In addition to that, an advanced engine control system in combination with all sensors was required to actively, accurately, repeatedly, and reliably control the system. This accomplishment in combination with competitive fuel economy numbers achieved with the vehicle will shift the main focus of the aging of the emission control system and evaluating the long term performance. This will be part of future work following efforts investigating different fuel sulfur levels in combination with ECS-A and ECS-B where the most promising configuration will be aged for a total of 2,050 hours.

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REFERENCE

[1] Geckler S., Tomazic D., et. al., “Development of a Desulfurization Strategy for a NOx Adsorber Catalyst System”, SAE Paper 2001-01-0510, 2001